

Practical Rocketry

The first rockets ever built, the fire-arrows of the Chinese, were not very reliable. Many just exploded on launching. Others flew on erratic courses and landed in the wrong place. Being a rocketeer in the days of the fire-arrows must have been an exciting, but also a highly dangerous activity.

Today, rockets are much more reliable. They fly on precise courses and are capable of going fast enough to escape the gravitational pull of Earth. Modern rockets are also more efficient today because we have an understanding of the scientific principles behind rocketry. Our understanding has led us to develop a wide variety of advanced rocket hardware and devise new propellants that can be used for longer trips and more powerful takeoffs.

Rocket Engines and Their Propellants

Most rockets today operate with either solid or liquid propellants. The word *propellant* does not mean simply fuel, as you might think; it means both *fuel* and *oxidizer*. The fuel is the chemical the rocket burns but, for burning to take place, an oxidizer (oxygen) must be present. Jet engines draw oxygen into their engines from the surrounding air. Rockets do not have the luxury that jet planes have; they must carry oxygen with them into space, where there is no air.

Solid rocket propellants, which are dry to the touch, contain both the fuel and oxidizer combined together in the chemical itself. Usually the fuel is a mixture of hydrogen compounds and carbon and the oxidizer is made up of oxygen compounds. Liquid propellants, which are often gases that have been chilled until they turn into liquids, are kept in separate containers, one for the fuel and the other for the oxidizer. Just before firing, the fuel and oxidizer are mixed together in the engine.

A *solid-propellant rocket* has the simplest form of engine. It has a *nozzle*, a *case*, *insulation*, *propellant*, and an *igniter*. The case of the engine is usually a relatively thin metal that is lined with insulation to keep the propellant from burning through. The propellant itself is packed inside the insulation layer.

Many solid-propellant rocket engines feature a hollow core that runs through the propellant. Rockets that do not have the hollow core must be ignited at the lower end of the propellants and burning proceeds gradually from one end of the rocket to the other. In all cases, only the surface of the propellant burns. However, to get higher thrust, the hollow core is used. This increases the



surface of the propellants available for burning. The propellants burn from the inside out at a much higher rate, sending mass out the nozzle at a higher rate and speed. This results in greater thrust. Some propellant cores are star shaped to increase the burning surface even more.

To ignite solid propellants, many kinds of igniters can be used. Fire-arrows were ignited by fuses, but sometimes these ignited too quickly and burned the rocketeer. A far safer and more reliable form of ignition used today is one that employs electricity. An electric current, coming through wires from some distance away, heats up a special wire inside the rocket. The wire raises the temperature of the propellant it is in contact with to the combustion point.

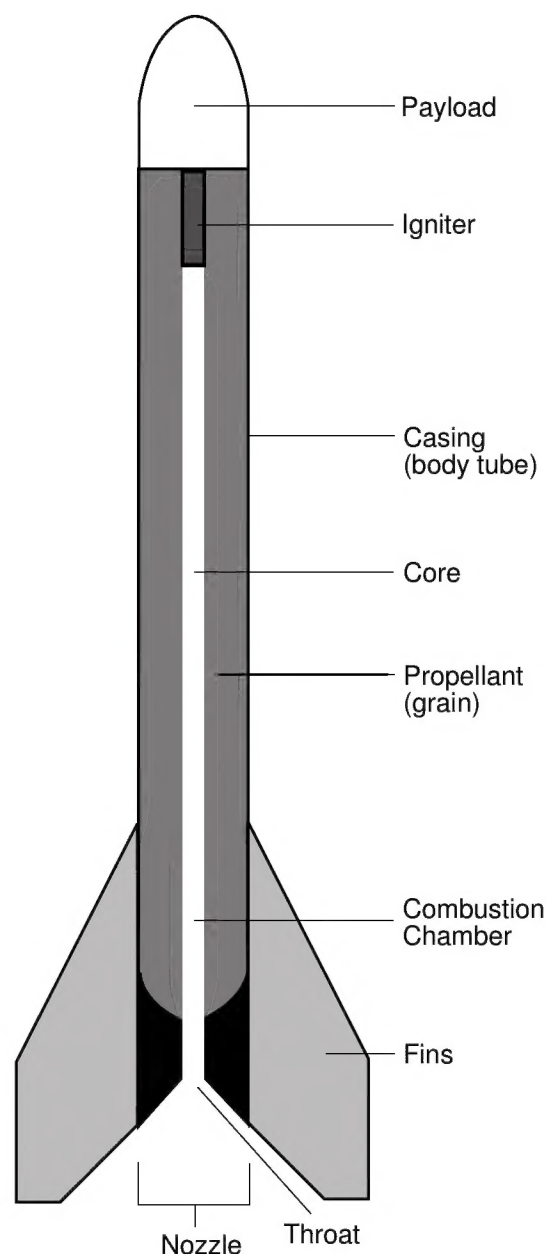
Other igniters are more advanced than the hot wire device. Some are encased in a chemical that ignites first, which then ignites the propellants. Still other igniters, especially those for large rockets, are rocket engines themselves. The small engine inside the hollow core blasts a stream of flames and hot gas down from the top of the core and ignites the entire surface area of the propellants in a fraction of a second.

The nozzle in a solid-propellant engine is an opening at the back of the rocket that permits the hot expanding gases to escape. The narrow part of the nozzle is the *throat*. Just beyond the throat is the exit cone.

The purpose of the nozzle is to increase the acceleration of the gases as they leave the rocket and thereby maximize the thrust. It does this by cutting down the opening through which the gases can escape. To see how this works, you can experiment with a garden hose that has a spray nozzle attachment. This kind of nozzle does not have an exit cone, but that does not matter in the experiment. The important point about the nozzle is that the size of the opening can be varied.

Start with the opening at its widest point. Watch how far the water squirts and feel the thrust produced by the departing water. Now reduce the diameter of the opening, and again note the distance the water squirts and feel the thrust. Rocket nozzles work the same way.

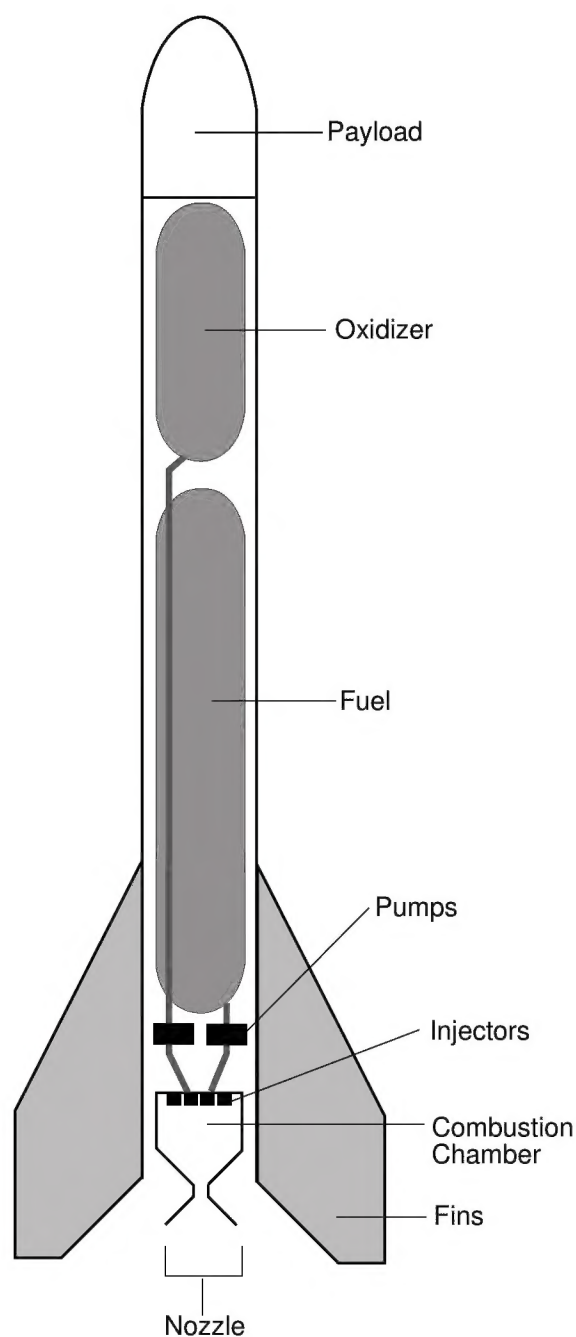
As with the inside of the rocket case, insulation is needed to protect the nozzle from the hot gases. The usual insulation is one that gradually erodes as the gas passes through. Small pieces of the insulation get very hot and break away from the nozzle. As they are blown away, heat is carried away with them.



Solid Propellant Rocket

The other main kind of rocket engine is one that uses liquid propellants, which may be either pumped or fed into the engine by pressure. This is a much more complicated engine, as is evidenced by the fact that solid rocket engines were used for at least seven hundred years before the first successful liquid engine was tested. Liquid propellants have separate storage tanks—one for the fuel and one for the oxidizer. They also have a *combustion chamber*, and a nozzle.





Liquid Propellant Rocket

The fuel of a liquid-propellant rocket is usually kerosene or liquid hydrogen; the oxidizer is usually liquid oxygen. They are combined inside a cavity called the combustion chamber. Here the propellants burn and build up high temperatures and pressures, and the expanding gas escapes through the nozzle at the lower end. To get the most power from the propellants, they must be mixed as completely as possible. Small *injectors* (nozzles) on the roof of the chamber spray and mix the propellants at the same time. Because the

chamber operates under high pressures, the propellants need to be forced inside. Modern liquid rockets use powerful, lightweight turbine pumps to take care of this job.

With any rocket, and especially with liquid-propellant rockets, weight is an important factor. In general, the heavier the rocket, the more the thrust needed to get it off the ground. Because of the pumps and fuel lines, liquid engines are much heavier than solid engines.

One especially good method of reducing the weight of liquid engines is to make the exit cone of the nozzle out of very lightweight metals. However, the extremely hot, fast-moving gases that pass through the cone would quickly melt thin metal. Therefore, a cooling system is needed. A highly effective though complex cooling system that is used with some liquid engines takes advantage of the low temperature of liquid hydrogen. Hydrogen becomes a liquid when it is chilled to -253°C . Before injecting the hydrogen into the combustion chamber, it is first circulated through small tubes that lace the walls of the exit cone. In a cutaway view, the exit cone wall looks like the edge of corrugated cardboard. The hydrogen in the tubes absorbs the excess heat entering the cone walls and prevents it from melting the walls away. It also makes the hydrogen more energetic because of the heat it picks up. We call this kind of cooling system *regenerative cooling*.

Engine Thrust Control

Controlling the thrust of an engine is very important to launching payloads (cargoes) into orbit. Thrusting for too short or too long of a period of time will cause a satellite to be placed in the wrong orbit. This could cause it to go too far into space to be useful or make the satellite fall back to Earth. Thrusting in the wrong direction or at the wrong time will also result in a similar situation.

A computer in the rocket's guidance system determines when that thrust is needed and turns the engine on or off appropriately. Liquid engines do this by simply starting or stopping the flow of propellants into the combustion chamber. On more complicated flights, such as going to the Moon, the engines must be started and stopped several times.

Some liquid-propellant engines control the amount of engine thrust by varying the amount of propellant that enters the combustion chamber. Typically the engine thrust varies for controlling the acceleration experienced by astronauts or to limit the aerodynamic forces on a vehicle.



Solid-propellant rockets are not as easy to control as liquid rockets. Once started, the propellants burn until they are gone. They are very difficult to stop or slow down part way into the burn. Sometimes fire extinguishers are built into the engine to stop the rocket in flight. But using them is a tricky procedure and does not always work. Some solid-fuel engines have hatches on their sides that can be cut loose by remote control to release the chamber pressure and terminate thrust.

The burn rate of solid propellants is carefully planned in advance. The hollow core running the length of the propellants can be made into a star shape. At first, there is a very large surface available for burning, but as the points of the star burn away, the surface area is reduced. For a time, less of the propellant burns, and this reduces thrust. The *Space Shuttle* uses this technique to reduce vibrations early in its flight into orbit.

NOTE: Although most rockets used by governments and research organizations are very reliable, there is still great danger associated with the building and firing of rocket engines. Individuals interested in rocketry should **never** attempt to build their own engines. Even the simplest-looking rocket engines are very complex. Case-wall bursting strength, propellant packing density, nozzle design, and propellant chemistry are all design problems beyond the scope of most amateurs. Many home-built rocket engines have exploded in the faces of their builders with tragic consequences.

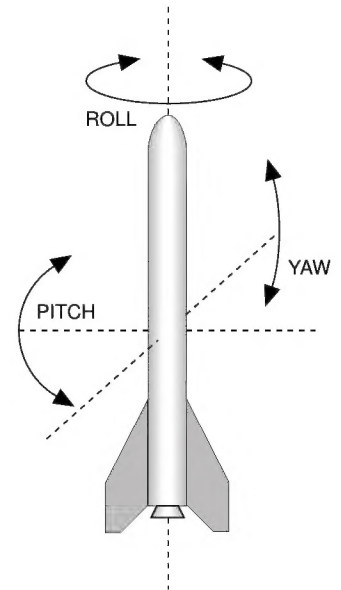
Stability and Control Systems

Building an efficient rocket engine is only part of the problem in producing a successful rocket. The rocket must also be stable in flight. A stable rocket is one that flies in a smooth, uniform direction. An unstable rocket flies along an erratic path, sometimes tumbling or changing direction. Unstable rockets are dangerous because it is not possible to predict where they will go. They may even turn upside down and suddenly head back directly to the launch pad.

Making a rocket stable requires some form of control system. Controls can be either active or passive. The difference between these and how they work will be explained later. It is first important to understand what makes a rocket stable or unstable.

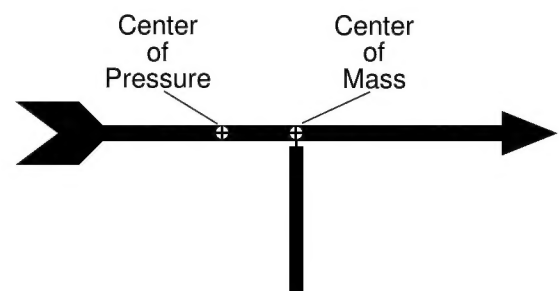
All matter, regardless of size, mass, or shape, has a point inside called the *center of mass* (CM). The center of mass is the exact

spot where all of the mass of that object is perfectly balanced. You can easily find the center of mass of an object such as a ruler by balancing the object on your finger. If the material used to make the ruler is of uniform thickness and density, the center of mass should be at the halfway point between one end of the stick and the other. If the ruler were made of wood, and a heavy nail were driven into one of its ends, the center of mass would no longer be in the middle. The balance point would then be nearer the end with the nail.



The center of mass is important in rocket flight because it is around this point that an unstable rocket tumbles. As a matter of fact, any object in flight tends to tumble. Throw a stick, and it tumbles end over end. Throw a ball, and it spins in flight. The act of spinning or tumbling is a way of becoming stabilized in flight. A Frisbee will go where you want it to only if you throw it with a deliberate spin. Try throwing a Frisbee without spinning it. If you succeed, you will see that the Frisbee flies in an erratic path and falls far short of its mark.

In flight, spinning or tumbling takes place around one or more of three axes. They are called *roll*, *pitch*, and *yaw*. The point where all three of these axes intersect is the center of mass. For



rocket flight, the pitch and yaw axes are the most important because any movement in either of these two directions can cause the rocket to go off course. The roll axis is the least important because movement along this axis will not affect the flight path. In fact, a rolling motion will help stabilize the



rocket in the same way a properly passed football is stabilized by rolling (spiraling) it in flight. Although a poorly passed football may still fly to its mark even if it tumbles rather than rolls, a rocket will not. The action-reaction energy of a football pass will be completely expended by the thrower the moment the ball leaves the hand. With rockets, thrust from the engine is still being produced while the rocket is in flight. Unstable motions about the pitch and yaw axes will cause the rocket to leave the planned course. To prevent this, a control system is needed to prevent or at least minimize unstable motions.

In addition to center of mass, there is another important center inside the rocket that affects its flight. This is the *center of pressure* (CP). The center of pressure exists only when air is flowing past the moving rocket. This flowing air, rubbing and pushing against the outer surface of the rocket, can cause it to begin moving around one of its three axes. Think for a moment of a weather vane. A weather vane is an arrow-like stick that is mounted on a rooftop and used for telling wind direction. The arrow is attached to a vertical rod that acts as a pivot point. The arrow is balanced so that the center of mass is right at the pivot point. When the wind blows, the arrow turns, and the head of the arrow points into the oncoming wind. The tail of the arrow points in the downwind direction.

The reason that the weather vane arrow points into the wind is that the tail of the arrow has a much larger surface area than the arrowhead. The flowing air imparts a greater force to the tail than the head, and therefore the tail is pushed away. There is a point on the arrow where the surface area is the same on one side as the other. This spot is called the center of pressure. The center of pressure is not in the same place as the center of mass. If it were, then neither end of the arrow would be favored by the wind and the arrow would not point. The center of pressure is between the center of mass and the tail end of the arrow. This means that the tail end has more surface area than the head end.

It is extremely important that the center of pressure in a rocket be located toward the tail and the center of mass be located toward the nose. If they are in the same place or very near each other, then the rocket will be unstable in flight. The rocket will then try to rotate about the center of mass in the pitch and yaw axes, producing a dangerous situation. With the center of pressure located in the right place, the rocket will remain stable.

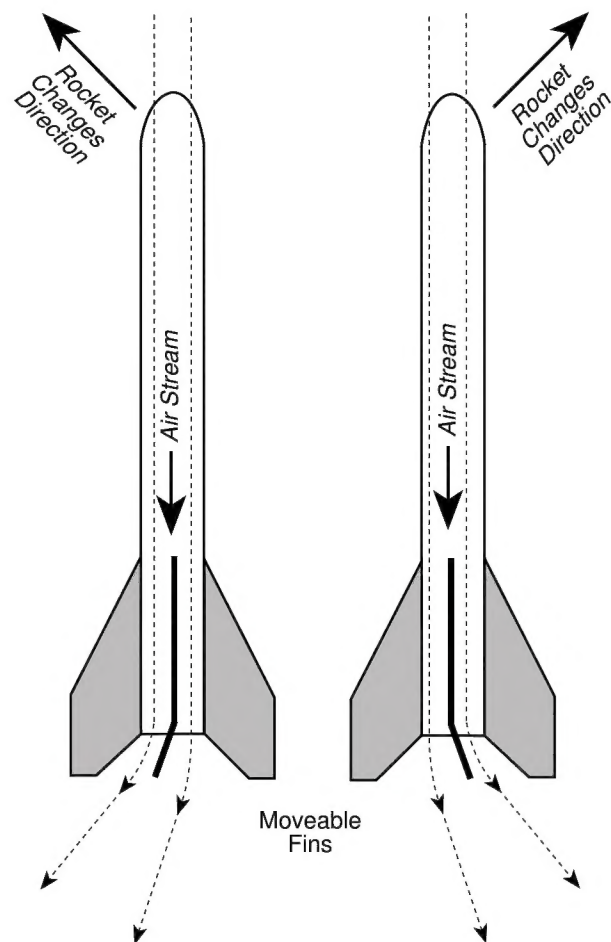
Control systems for rockets are intended to keep a rocket stable in flight and to steer it. Small

rockets usually require only a stabilizing control system. Large rockets, such as the ones that launch satellites into orbit, require a system that not only stabilizes the rocket, but also enable it to change course while in flight.

Controls on rockets can either be active or passive. *Passive controls* are fixed devices that keep rockets stabilized by their very presence on the rocket's exterior. *Active controls* can be moved while the rocket is in flight to stabilize and steer the craft.

The simplest of all passive controls is a stick. The Chinese fire-arrows were simple rockets mounted on the ends of sticks. The stick kept the center of pressure behind the center of mass. In spite of this, fire-arrows were notoriously inaccurate. Before the center of pressure could take effect, air had to be flowing past the rocket. While still on the ground and immobile, the arrow might lurch and fire the wrong way.

Years later, the accuracy of fire-arrows was improved considerably by mounting them in a trough aimed in the proper direction. The trough



guided the arrow in the right direction until it was moving fast enough to be stable on its own.

As will be explained in the next section, the weight of the rocket is a critical factor in performance and range. The fire-arrow stick added too much dead weight to the rocket, and therefore limited its range considerably.

An important improvement in rocketry came with the replacement of sticks by clusters of lightweight fins mounted around the lower end near the nozzle. Fins could be made out of lightweight materials and be streamlined in shape. They gave rockets a dart-like appearance. The large surface area of the fins easily kept the center of pressure behind the center of mass. Some experimenters even bent the lower tips of the fins in a pinwheel fashion to promote rapid spinning in flight. With these "spin fins," rockets become much more stable in flight. But this design also produces more drag and limits the rocket's range.

With the start of modern rocketry in the 20th century, new ways were sought to improve rocket stability and at the same time reduce overall rocket

weight. The answer to this was the development of active controls. Active control systems included *vanes*, *movable fins*, *canards*, *gimbaled nozzles*, *vernier rockets*, *fuel injection*, and *attitude-control rockets*. Tilting fins and canards are quite similar to each other in appearance. The only real difference between them is their location on the rockets.

Canards are mounted on the front end of the rocket while the tilting fins are at the rear. In flight, the fins and canards tilt like rudders to deflect the air flow and cause the rocket to change course. Motion sensors on the rocket detect unplanned directional changes, and corrections can be made by slight tilting of the fins and canards. The advantage of these two devices is size and weight. They are smaller and lighter and produce less drag than the large fins.

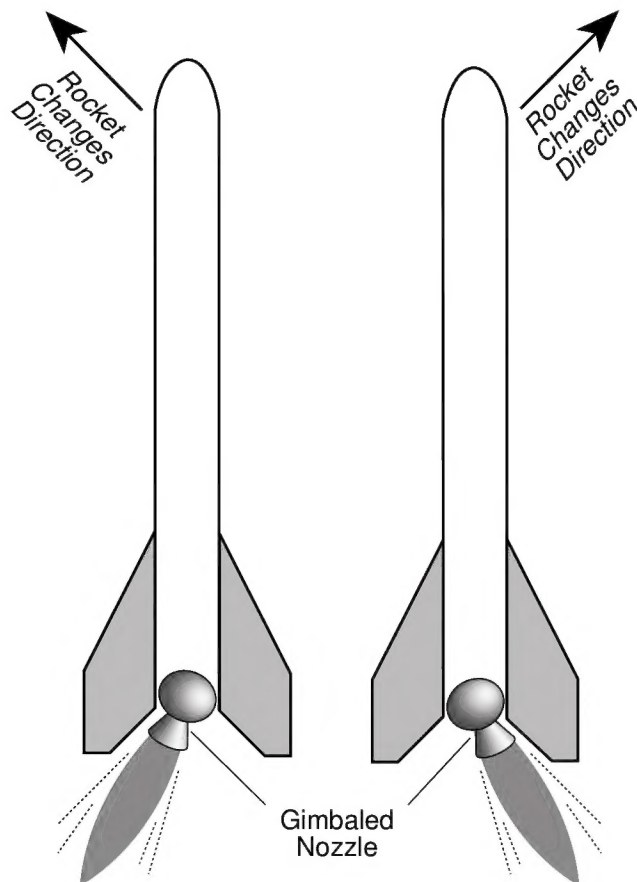
Other active control systems can eliminate fins and canards altogether. By tilting the angle at which the exhaust gas leaves the rocket engine, course changes can be made in flight. Several techniques can be used for changing exhaust direction.

Vanes are small finlike devices that are placed inside the exhaust of the rocket engine. Tilting the vanes deflects the exhaust, and by action-reaction the rocket responds by pointing the opposite way.

Another method for changing the exhaust direction is to gimbal the nozzle. A gimbaled nozzle is one that is able to sway while exhaust gases are passing through it. By tilting the engine nozzle in the proper direction, the rocket responds by changing course.

Vernier rockets can also be used to change direction. These are small rockets mounted on the outside of the large engine. When needed they fire, producing the desired course change.

In space, only by spinning the rocket along the roll axis or by using active controls involving the engine exhaust can the rocket be stabilized or have its direction changed. Without air, fins and canards have nothing to work upon. (Science fiction movies showing rockets in space with wings and fins are long on fiction and short on science.) While coasting in space, the most common kinds of active control used are attitude-control rockets. Small clusters of engines are mounted all around the vehicle. By firing the right combination of these small rockets, the vehicle can be turned in any direction. As soon as they are aimed properly, the main engines fire, sending the rocket off in the new direction.



Mass

Mass is another important factor affecting the performance of a rocket. The mass of a rocket can make the difference between a successful flight and just wallowing around on the launch pad. As a basic principle of rocket flight, it can be said that for a rocket to leave the ground, the engine must produce a thrust that is greater than the total mass of the vehicle. It is obvious that a rocket with a lot of unnecessary mass will not be as efficient as one that is trimmed to just the bare essentials.

For an ideal rocket, the total mass of the vehicle should be distributed following this general formula:

Of the total mass, 91 percent should be propellants; 3 percent should be tanks, engines, fins, etc.; and 6 percent can be the payload.

Payloads may be satellites, astronauts, or spacecraft that will travel to other planets or moons.

In determining the effectiveness of a rocket design, rocketeers speak in terms of mass fraction (MF). The mass of the propellants of the rocket divided by the total mass of the rocket gives mass fraction:

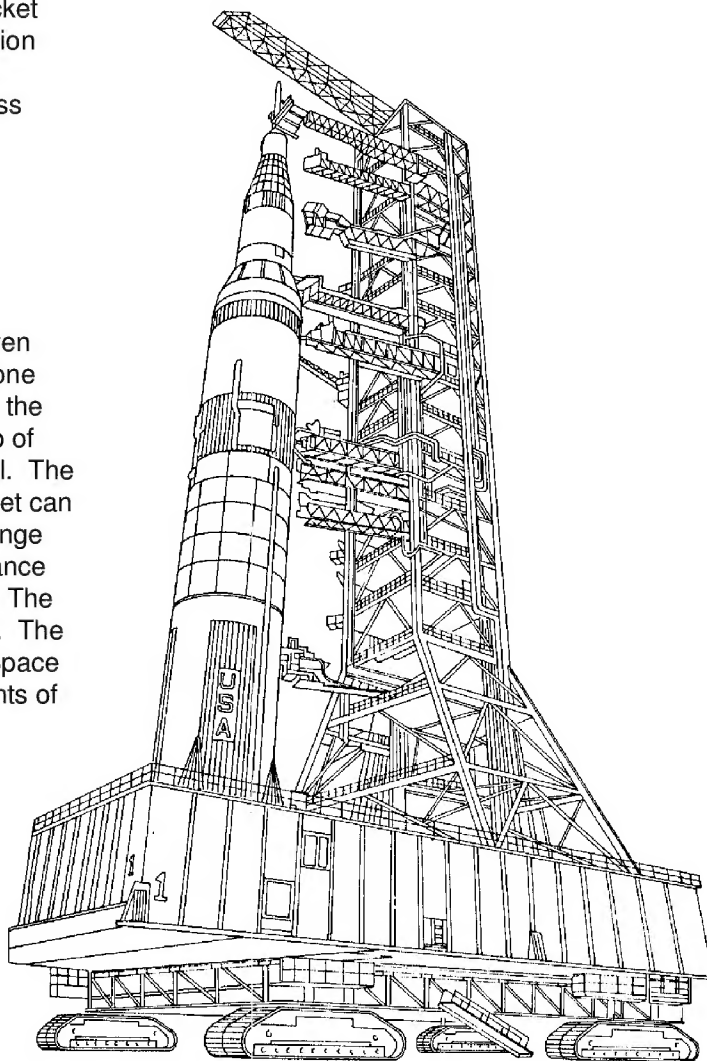
$$MF = \frac{\text{mass of propellants}}{\text{total mass}}$$

The mass fraction of the ideal rocket given above is 0.91. From the mass fraction formula one might think that an MF of 1.0 is perfect, but then the entire rocket would be nothing more than a lump of propellants that would simply ignite into a fireball. The larger the MF number, the less payload the rocket can carry; the smaller the MF number, the less its range becomes. An MF number of 0.91 is a good balance between payload-carrying capability and range. The Space Shuttle has an MF of approximately 0.82. The MF varies between the different orbiters in the Space Shuttle fleet and with the different payload weights of each mission.

Large rockets, able to carry a spacecraft into space, have serious weight problems. To reach space and proper orbital velocities, a great deal of propellant is needed; therefore, the tanks, engines, and associated hardware become larger. Up to a point, bigger rockets can carry more payload than smaller rockets, but when they become too large their structures weigh them down too much, and the mass fraction is reduced to an impossible number.

A solution to the problem of giant rockets weighing too much can be credited to the 16th-century fireworks maker Johann Schmidlap. Schmidlap attached small rockets to the top of big ones. When the large rocket was exhausted, the rocket casing was dropped behind and the remaining rocket fired. Much higher altitudes were achieved by this method. (The Space Shuttle follows the step rocket principle by dropping off its solid rocket boosters and external tank when they are exhausted of propellants.)

The rockets used by Schmidlap were called step rockets. Today this technique of building a rocket is called *staging*. Thanks to staging, it has become possible not only to reach outer space but the Moon and other planets too.



Saturn 5 rocket being transported to the launch pad.